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14. **ABSTRACT**
The goal of this work is to develop and test new technologies that will break down the barriers that block more surgeons from attaining and continuing to practice (without injury or pain) high levels of skill in minimally invasive surgery (MIS). This project will develop new technology by concentrating on three major research thrusts: Smart Image: the project will develop and evaluate new approaches for extracting, fusing, and presenting information cues from imagery and other data sources; Configurable Display: the project will develop new approaches for presenting existing data (video, CT data) and extracted cues (3D reconstruction, haptic cues, etc.) to the user within a flexible, configurable display environment; Ergonomic Assessment: the project will use existing technology and build new techniques as needed to acquire crucial ergonomic data relative to key factors of patient position, technology configuration, and instrument design.

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REVEAL: Reconstruction, Enhancement, Visualization, and Ergonomic Assessment for Laparoscopy

2005 Annual Report

1. Introduction

Information cues available in laparoscopy and other forms of minimally invasive surgery are impoverished relative to cues available in open surgery. Acquiring surgical skill in such an environment is extremely challenging. Even after mastery, continued practice can lead to problems for the surgeon as indicated by frequent incidence of pain and injury associated with laparoscopy. The long-term impact on the surgeon performing these procedures is largely unknown.

The goal of this work is to develop and test new technologies that will break down the barriers that block more surgeons from attaining and continuing to practice (without injury or pain) high levels of skill in MIS. This project will develop new technology by concentrating on three major research thrusts:

- **Smart Image**: the project will develop and evaluate new approaches for extracting, fusing, and presenting information cues from imagery and other data sources.
- **Configurable Display**: the project will develop new approaches for presenting existing data (video, CT data) and extracted cues (3D reconstruction, haptic cues, etc.) to the user within a flexible, configurable display environment
- **Ergonomic Assessment**: the project will use existing technology and build new techniques as needed to acquire crucial ergonomic data relative to key factors of patient position, technology configuration, and instrument design.

2. Major Accomplishments

In this section we provide a functional view of major tasks accomplished during the 2005 project year. These include (1) deployment of the REVEAL display system and tool suite in the University of Maryland Medical Center's Simulation Center, (2) REVEAL tool suite improvements, (3) stereo video display technology upgrades, (4) stereo probe calibration, (5) performance modeling and analysis, and (6) enhanced experimental tools for cognitive ergonomics experiments.

Deployment of the REVEAL Display System at UMMC Simulation Center

A combined motion capture/immersive display system has been deployed in the Simulation Center at the University of Maryland Medical Center. The system was deployed in a decommissioned OR in the South hospital that is being refit for use as a simulation, training and research center. The deployed system consists of custom fixtures, a self-calibrating immersive display similar to that deployed in the UK REVEAL lab, and a Vicon motion capture system. The system supports the ergonomic assessment portion of REVEAL at the University of Maryland.

Custom Fixtures. A custom-built truss system provides a flexible mounting system for locating cameras, projectors and Vicon sensors at optimal positions within the laboratory environment. The environment can be reconfigured rapidly based on the demands of a particular experiment using quick-release clamps.

Self-Calibrating Immersive Display. A self-calibrating immersive display with a curvilinear rear-projection screen for use in monocular and stereoscopic display configurations was deployed. The basic hardware/software environment is similar to that deployed in the University of Kentucky's REVEAL laboratory. Changes have been made where the unique constraints of deployment in a simulated OR have diverged from our general purpose laboratory set-up. In particular, the system uses a smaller wrap-around screen designed to maximize the immersive display experience for the surgical team in their customary positions during a procedure.

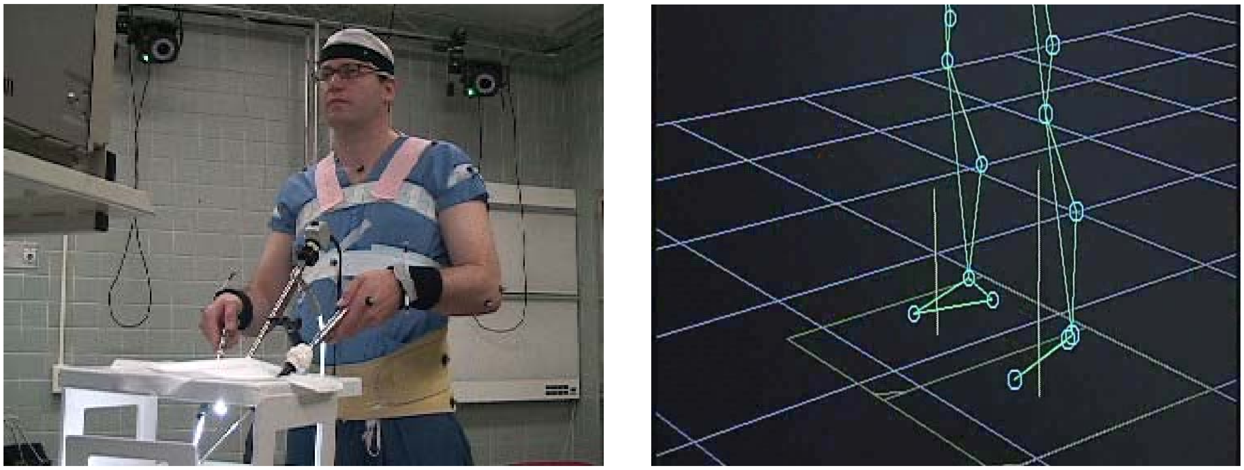

Fig. 1: The subject on the left is being tracked by the Vicon camera system. The system detects joint positions and can estimate angles in a unified 3D coordinate frame.

Equipment and Environment: Vicon motion capture system. A Vicon motion capture system is on-line, providing sub-millimeter precision for the location of objects in three-dimensional space. This system is being used to study instrument and joint positions during laparoscopic procedures to assess the physical requirements of laparoscopy (Fig. 1). This data will be used to produce assessment-oriented data describing the actual demands of current practice, and to design improved surgical gestures that reduce the physical demands of the tasks.

This Vicon system consists of 12 high-speed, high-resolution, infrared, digital cameras. For custom installation of these cameras, a truss system was set up. These cameras have been positioned, aimed, and focused to optimize the size of motion capture volume and the recognition of the 9.5mm markers coated with retro-reflective materials that are placed on experiment participants. Two force plates purchased from AMTI (Advanced Mechanical Technology, Inc., Watertown, MA) have been placed on the floor of the lab. Analog force and moment data are captured, synchronized, and stored through ViconPeak's analog data capture system. Using a mini-DV camcorder, this system also captures images of upper-body movement and stores them with motion capture data. An additional video capture device is used to record endoscopic images used for monitoring instrument movement in the trainer box and evaluating surgical performance. A 16 channel electromyography (EMG) recorder has been purchased to monitor the timing and relative amplitude of muscle activities. This EMG system uses pre-amplifiers integrated into electrodes so signal-to-noise input ratio is enhanced.

Initial Experiments: Pegboard transfer, pattern cutting, endo-loop placement, and suturing/intracorporeal knot tying, four of the five tasks that comprise the Fundamentals of Laparoscopic Surgery (FLS)–the official examination program used by the Society of American Gastrointestinal Endoscopic Surgeons (SAGES)–are being and have been used in our experiments (see example endoscopic images in Fig. 2). Numerous researchers have already validated well that strong correlations between test scores and surgical levels can be obtained through performance analysis of these FLS tasks. Seven, right-handed surgeons with different levels of minimally invasive surgery (MIS) experience were recruited to perform the tasks. During the experiment the surgeons stood with one foot on each force plate. So that surgeons could maintain the correct elbow joint angle while holding surgical instruments at rest, the surgical trainer box was mounted on a height-adjustable platform. A standard CRT monitor that displayed endoscopic images from zero-degree scope was located at eye level in front of the participants. Wearing medical scrub, the surgeons had 39 reflective markers placed on body landmarks so that their body movements could be reconstructed using motion capture technique. Marker placement followed the ViconPeak guidelines for the Plug-In-Gait (PIG) model. Movements of body segments were captured, and joint movements were shown in three rotations - flexion/extension, abduction/adduction, and internal/external. Force plates recorded data of ground reaction forces and moments to provide information for postural stability analysis.

Fig 2: Endoscopic views of baseline tasks

Current Experimental Research Outcomes

Optimizing joint kinematics will most likely allow MIS surgeons to achieve better surgical performance. Joint kinematics characterized by range of motion (ROM), mean joint angle (MJA), and mean joint movement amplitude (MJMA) were correlated to performance time during the FLS pegboard transfer task. MJA varied with different performance skill. Participants requiring the most time to perform showed more mean flexion angles ($r=.684$, $P<.05$) at the left elbow while maintaining approximately 90 degrees at the right elbow. Regarding the left wrist, more skilled participants, requiring the least time, showed more external rotations ($r=.680$, $p<.05$) while less skilled subjects maintained the neutral position. Less skilled subjects showed more external rotation at the right wrist ($r=-.751$, $p<.05$). ROM and MJMA did not differentiate performance skill levels. This study suggests the development of further investigations on joint movement patterns to formulate joint control strategies for optimal laparoscopic surgery training [4].

It is very important for MIS surgeons to maintain proper postural stability for better surgical performance. Postural stability was correlated to surgical skill level represented by performance time during pegboard transfer, pattern cutting, and endo-loop placement tasks. Center of Pressure (COP) was derived separately from each force plate and then combined to obtain overall COP which showed anterior-posterior (A-P) and medial-lateral (M-L) sway. It was found that each FLS task required unique postural control adjustment. More experienced participants showed smaller COP excursion in A-P direction during pegboard transfer ($r=.912$, $p<.05$) and in M-L direction during pattern cutting ($r=7.888$, $P<.05$). During endo-loop placement, COP excursion was inversely correlated with performance time ($r=-.884$, $P<.05$, $r=-.824$, $P<.05$). This study emphasized that optimized ergonomics should be determined by individual task [5].

When suturing/intracorporeal knot tying, the most difficult of the FLS tasks, was evaluated, joint ROM was used to characterize joint kinematics. During this task, it was found that more skilled surgeons relied less on shoulder movement than less skilled participants. Expert surgeons showed smaller ROM at the dominant wrist and greater ROM at the non-dominant wrist. This research serves as the starting point of more detailed analysis of surgical movement that characterizes the joint movement and joint coordination of expert surgeons [6].

Previous studies in surgical ergonomics have shown that instrument usage, task difficulty, and subject skill level can be correlated to postural stability. However, these studies did not consider the possibility that surgeons may strategically change their stance or joint movement to achieve better surgical outcomes while potentially subjecting themselves to greater kinematic risk. In our study, one highly experienced and skilled surgeon reported the development of carpal tunnel syndrome in both of his wrists. highly experienced and skilled surgeon Still, this participant was able to finish both the pegboard transfer and pattern-cutting tasks significantly faster than others,

within a minute for each task. To minimize wrist flexion during the pegboard transfer task, the surgeon increased the abduction angle of his shoulder so that his hand and forearm aligned. During pattern cutting, the subject maintained his lower body position and stance while twisting his torso in a strategy that appeared to stabilize a tangential direction in relation to the cutting while maintaining a fixed orientation of forearm, wrist, and hand. In a different trial when circle-cutting was the task, the subject changed his stance primarily by shifting foot position as needed in order to obtain better approach angles for the scissors. These compensatory and strategic movements caused increase in his overall postural sway, yet they did not necessarily represent postural instability. This case study demonstrated that poor postural stability or joint kinematics do not necessarily correlate to poor performance but may instead be positive compensatory or strategic movements. Therefore, background information about participants, which might, for instance, include joint impairment, should be considered as important ergonomic elements, the correlations of which may lead to more accurate and specific conclusions about optimal postural stability and joint kinematics for minimally invasive surgeons [7].

Custom Development within Experimental Setup: Markers must be placed so that the best camera recognition and body segment definition are obtained. For our experiments, the ViconPeak marker placement guidelines were followed. The ViconPeak Plug-In-Gait marker set was originally designed for analysis of lower and upper body motion in conventional situations. Expecting that more obstacles would be located between markers and cameras in a surgical environment, we have developed custom marker placement that is achieved by using clustered markers. For better data capturing, three or four markers are grouped together and attached to a body segment toward which the cameras are pointed. To define a segment, there should be three markers in each segment. When one marker of a segment is lost during data collection, the segment cannot be defined and biomechanical model stops working. Therefore, one or more extra markers in each segment can be used to missing marker problem and this also supports the need of custom marker. The Plug-In-Gait biomechanical model that calculates kinematic data including joint angles cannot be used as is with a custom marker set. The International Society of Biomechanics (ISB) just recently published an article suggesting new marker sets, segment definitions, and angle calculations [8]. Plug-In-Gait has been shown to cause a well-known surgical movement problem called 'gimbal-lock', which is a unique angle of the shoulder joint. Therefore, a biomechanical model that incorporates new ISB recommendations and custom marker sets is now being developed here as a part of REVEAL project.

REVEAL Tool Suite Improvements

REVEAL tool suite development efforts continued with an emphasis on deployment tasks and usability. New features deployed include a graphical user interface for the VIBE display system, an integrated video display application for endoscopic video streams, support for digital video streams, and improved installation tools.

Graphical User Interface. The REVEAL development team has implemented a graphical user interface (GUI) to control the self-calibrating display system. Previously, a set of shell scripts had to be executed at the command line to carry out calibration, display and application-driver functions. These functions are now included in an intuitive GUI that non-technical staff can use to control the system using mouse-clicks on descriptive drop-down menus and buttons.

Integrated video display application for endoscope video streams. An OpenGL application that will read video input streams from endoscope controller outputs has been created that handles either monocular or stereoscopic video input. This application enables the display of mono- or stereo image streams using the self-calibrating VIBE display system.

Digital video support. The range of input devices handled by the streaming video application has been expanded to include digital video input. Previously input had to be supplied through an analog connection to a WinTV interface card. This is a proprietary TV tuner card that severely restricted the types of cameras that could integrated with our system. The addition of digital video support allows data to be input via a IEEE 1394 (FireWire) interface from any FireWire capable video device. FireWire is the most common standard in use today for digital video input to computers.

Installation tools. A set of hands-off installation tools were created that simplify the installation of the REVEAL tools on a target system. The tools detect the existing configuration on the target system and make necessary

connections between existing resource locations and the new system, as well as notifying the installer of any missing prerequisite packages.

Stereo Video Display Technology Upgrades

During 2005 we made two changes to the equipment of our laboratory that significantly improved the quality of displayed stereo images. These included the use of glass filter material for polarizing the left and right channels, and the purchase of polarity-preserving screen fabric.

Glass filters. The original plastic polarizing filters that we used to project independent left and right visual channels using polarized light proved inadequate for our application. This was due largely to the extreme heat generated by the COTS DLP projectors we are using. During 2005 we replaced the plastic filters with glass filter material, eliminating problems of distortion of the filter surface and eliminating the risk of fire from burning filter material.

Polarity preserving screen. Our rear-projection screen was upgraded using polarity-preserving screen fabric that significantly improves channel separation for projected stereo images.

Stereo Probe Calibration

A Stereoscopic Endoscope is an endoscope with two optical paths, either separate or shared, creating two images related to one another by a measurable disparity shift. Such an endoscope can be used to generate a stereoscopic view for a surgeon, as with the DaVinci robot in use today. In order to use such an endoscope for metric measurement of structures in the operative field, it is necessary to calibrate the dual optical paths according to a camera model. Once calibrated, it is possible to use stereo reconstruction in order to recover Euclidean metric measurements from the endoscopic images.

This measurement capability is extremely valuable in a number of contexts where it is otherwise difficult to gauge the size and scale of the operative field. For example, Fig. 3 shows an image from a laparoscopic ventral and incisional hernia repair where a small patch of mesh is sewn into the abdominal wall to repair the defect that allowed the herniation to occur. Intraoperatively, the size of the defect must be determined so that a mesh patch of the proper size can be introduced into the surgical site through a trocar. The determination of the dimensions of the defect is currently performed using a tape measure, manipulated using graspers. This step requires the introduction and removal of the tape to perform the measurement. Using a stereoscopic laparoscope and real-time reconstruction of the three-dimensional anatomy allows such measurements to be taken on the imagery using virtual measuring tapes.

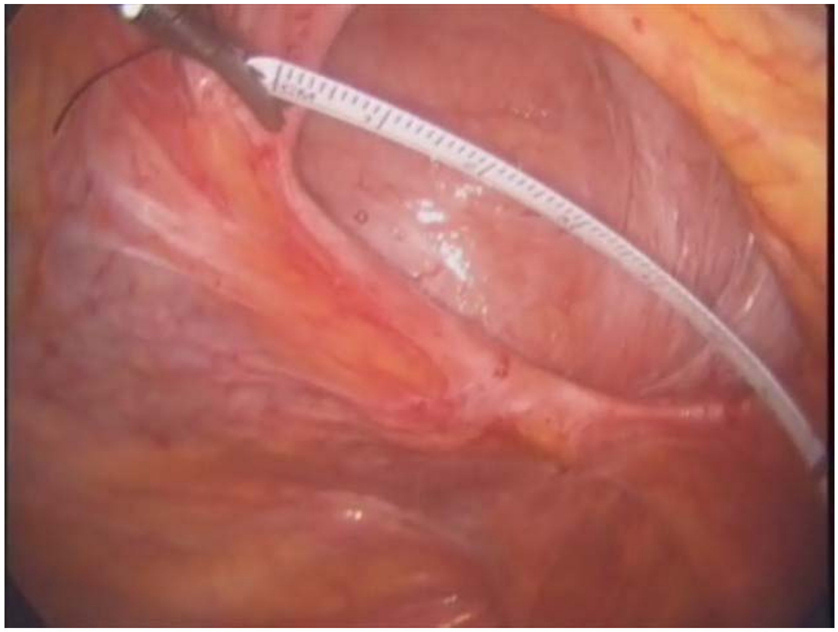

Fig. 3: Laparoscopic view of the measurement tape for hernia repair

In this work we report calibration results for a stereoscopic endoscope that support the ability to make instantaneous measurements in the image from a single stereo pair. Our initial experiments also indicate that a the stereo measurement accuracy can be improved by combining the estimates from stereo pairs with monocular-view structure-from-motion estimates derived from tracked features over a number of frames.

Our work yields metric information to reduce the difficulty in estimating sizes without the need for a reference object in the scene or an external tracking system. The stereoscopic system can provide metric information even when only one image stream from the scope is in fact necessary during the procedure (if there is a situation where stereo display for the surgeon is not a requirement).

The lens system of the stereoscopic endoscope where both views use the same optical path creates a calibration challenge because of the difficulty in modelling the system directly as a pinhole. We have developed a staged calibration process that first removes global non-linear distortion from the image by calculating an optimized global solution to a polynomial radial distortion model. We use three free parameters in the model, including two parameters for the radial decentering and a third radially symmetric coefficient. The first stage uses images of straight lines in order to solve for an optimal set of parameters that minimizes the global distortion according to the model. The constraint is that straight lines in the scene must remain straight in the image under the pinhole perspective projection.

The solution to the distortion model allows the input images to be unwarped according to the parameters of the radial distortion model, which serves as input to the second stage of the calibration. This stage uses known fiducials on targets in order to solve a system of equations for the intrinsic parameters of the camera. Once this optimization has been completed, it is possible to use the two calibrated optical paths for stereo matching (in a single corresponding frame) and 3D reconstruction.

Using a single stereo pair, a matching structure yields a 3D point. We augment this measurement with a set of equations over multiple frames that assume the matching structure can be tracked for some set of frames. By combining 2D and 3D constraints as position estimates from stereo and estimates from 2D feature-based structure-from-motion equations we are able to achieve a tighter bound on the accuracy of the measurement process.

Results from each stage of the calibration process show (1) how distortion is removed from the stereo pair; (2) the intrinsic parameters calculated from the unwarped images of known fiducial patterns; (3) the error in the 3D reconstruction of known points in the scene; and (4) estimates of the relative error for measurements in the operative field at known distances from the scope.

With respect to (1), once the global unwarp is applied to the image the mean error in pixel coordinates is 5 (reduced from as much as 20-30 for many scopes). The intrinsic parameters calculated from these unwarped images yield projection matrices with mean reprojection errors of 3 pixels (for the set of input values). Using these matrices for stereo reconstruction, the mean error in the 3D position of reconstructed points is 8 mm near the center of the image field to 15 mm near the edge. These measurements are relative to depths across the working volume of approximately 125 mm. The results indicate that bench calibration of stereoscopic endoscopes can be done to a degree that is good enough to make instantaneous measurements for procedures like hernia repairs and estimates of sizes and areas of regions of interest. Errors in measurements from stereoscopic pairs alone lead us to examine the fusion of data over multiple frames using structure-from-motion in order to narrow the error profile and extend the applicability of the feature to micro features. Our preliminary results in the fusion of measurements (using multiple frames and structure-from-motion) indicate we can narrow the accuracy to a mean error of 4 mm across the image field.

Bench calibration of stereoscopic endoscopes can provide a valuable way to make in-the-image instantaneous measurements from a single stereo pair with enough accuracy to save time in certain procedures where metric measurements are necessary for making decisions and recording anomalies. Errors in reconstruction are large enough that it warrants continued work on calibration methods and integration of second-order measurement equations (e.g., structure from motion, structured light) in order to narrow the error profile.

Performance Modeling and Analysis

In accordance with stated year two objectives, the creation of performance models and analysis of system performance were carried out for the display system. Image latency and image quality are critical factors determining end-user perceived quality for the display of surgical images, so we focused on these two areas: Image latency and image quality.

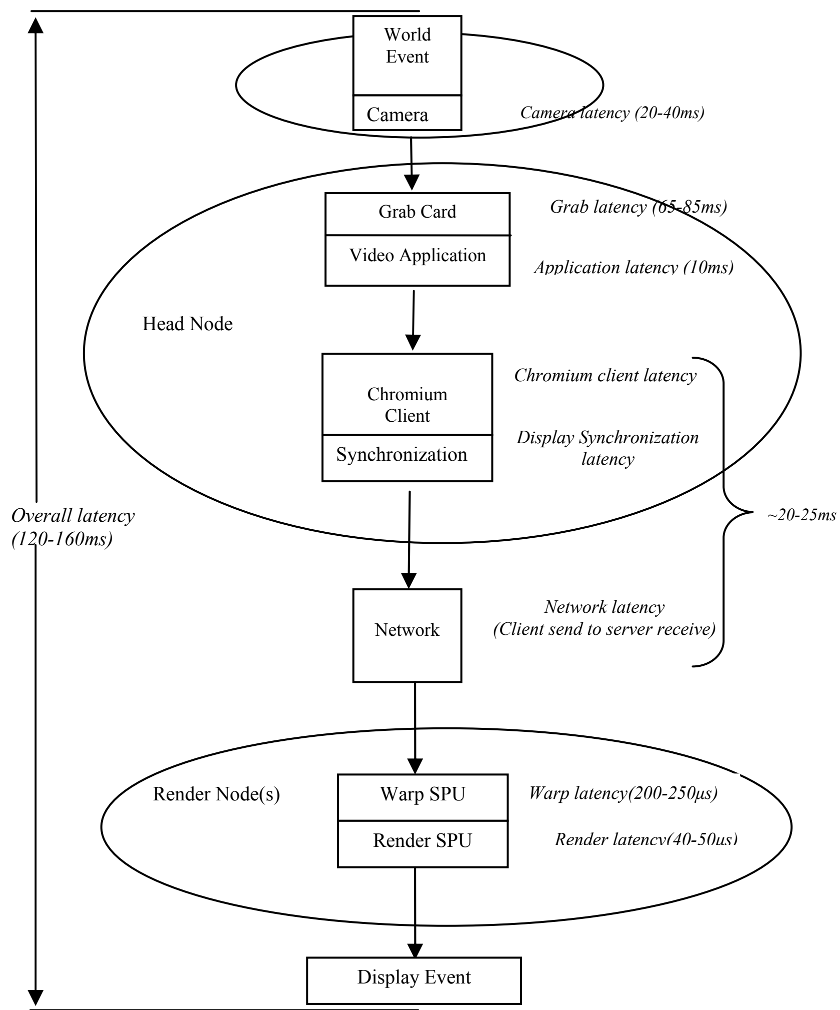

Fig. 4: Display System Latency Model with Experimental Timings

Figure 4 illustrates the chain of processing steps from initial world event (*i.e.,* any action in a scene observed by the camera) to final display. Experimentation with our current configuration yielded the quantitative latency values shown in the figure. Overall latency is currently running 120-160 ms. A generally accepted goal for latency is 100 ms or less, thus there is room for improvement in our current performance.

The area most likely to yield significant improvement is the image capture process at the beginning of the sequence of actions. As shown, 20-40 ms of latency is incurred just capturing and processing the image within the digital camera. Another 65-85 ms accumulates in the frame grabbing process followed by approximately 10 ms of latency for the OpenGL video capture and display application.

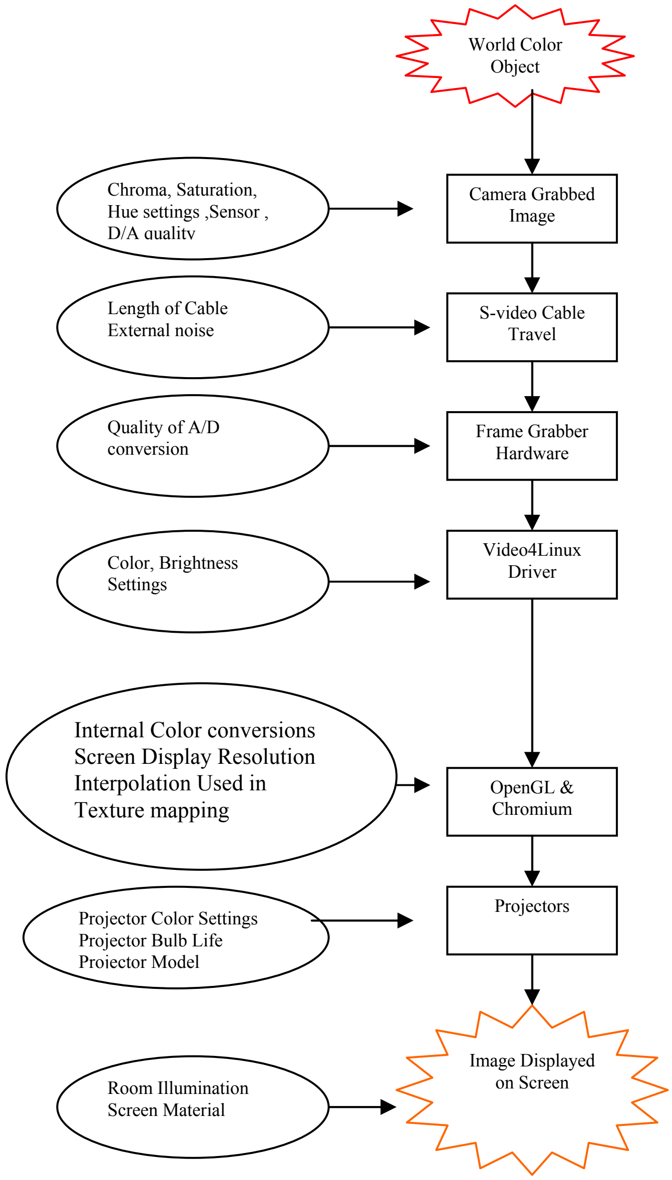

Fig. 5: Display System Color Reproduction Model

Figure 5 presents a preliminary model of image processing steps that may impact color reproduction. The accuracy of color reproduction is critical in the display of surgical images because variations in tissue coloring can indicate boundaries between anatomical structures, or they can indicate a boundary between healthy and diseased tissues. At present the experimental measurement and evaluation of color reproduction in our system is an open problem that we intend to address during Year 3.

Enhanced Experimental Tools for Cognitive Ergonomics Experiments

Our current work recognizes the need to emphasize both physical and cognitive ergonomics during the development and assessment of new visualization tools. There has been little precedent for the use of cognitive assessment tools in the context of laparoscopic surgery; therefore, we have been devoting considerable effort to developing and evaluating such outcome measures. These tools are specifically designed to determine whether technological innovations in the operating room have the following desired effects. Do they reduce the surgeon's mental workload? Do they reduce perceived stress? And do they enhance the surgeon's situation awareness?

The mental workload, stress, and situation awareness measures that we are currently testing must meet several criteria. They must be reliable and sensitive enough to allow assessments involving relatively few research participants (ultimately surgeons). They must also be easy to implement in the surgical environment. Finally, they must be accepted by the surgeons whose performance will be measured. To date, our research has focused on developing appropriate mental workload measures and testing them for sensitivity. However, we are also exploring the application of an existing stress measure, the Short Stress State Inventory (SSSI), and we are developing a novel situation awareness measure that involves testing the surgeon's ability to recover from interruptions.

Experimental Environment

During 2005 a second-generation software tool for cognitive ergonomics experiments was developed and deployed in the REVEAL lab. The new program represents a significant step toward realistically modeling laparoscopic surgical tasks for psychological study.

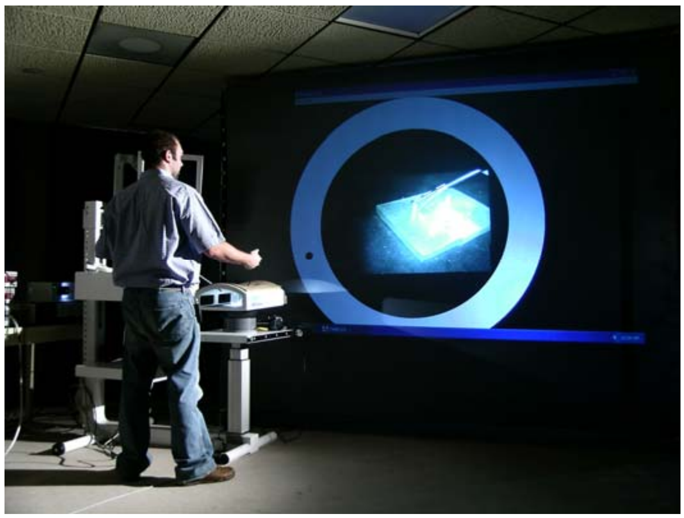

Fig. 6: Display of Enhanced Secondary Task Program

Figure 6 presents the new display layout using the tiled projected display to present images from the laparoscope. The primary task is now a standard minimally invasive surgery task involving manipulation of objects inside a black box using graspers. The secondary task is now confined to a pre-defined region (shown as a blue circle in the figure).

A further step toward realism was the elimination of computer mouse input. Surgeons typically use voice response systems to interact with computer systems intra-operatively, and we have employed that technology for identification of secondary task events. Now, instead of clicking a mouse button to signal the appearance of a secondary task item, the experimental subject simply speaks into a microphone which converts their voice into an input signal that the computer recognizes as a secondary task recognition event.

Development and Selection of Workload Measures

Our initial evaluation of mental workload measures took place in fall 2004. The NASA-TLX, a subjective measure composed of six rating scales and formerly validated in aviation environments, was evaluated using a simple manual control task that required precise positioning movements of a cursor on a computer monitor. We manipulated workload by inserting various lag times into the response of the display to control inputs by the subjects. Results indicated that the measure was sensitive to the increased effort required to manipulate the cursor with lags as small as 250 msec. This was true even though research participants were often unaware that lags of this duration were even present. In addition, the NASA-TLX was able to detect the statistically reliable workload increments with as few as four research participants.(for this particular display manipulation). This last finding is important given the

limited availability of surgeons to perform evaluation experiments. The NASA-TLX was therefore carried over to the current year's research, where it is being used in a simulated surgical environment.

We also developed and evaluated a secondary task measure requiring detection of slowly expanding circles presented to research participants' visual peripheries. The assumption behind this measure is that when a primary surgical task requires more effort, these peripheral targets will go undetected for longer periods of time. The advantage of such secondary tasks for workload assessment, compared to subjective measures, is that they are diagnostic of the specific types of mental workload that may be reduced or increased by changes in instrumentation. In our case, because of our focus on display innovation, we are seeking measures that are fairly specific to changes in visuospatial cognitive effort. Initial experiments using the lag task described above revealed that we needed to modify the eccentricity, growth rate, and contrast of the peripheral targets in order to make the task sufficiently sensitive. These modifications were made during the current year as we moved this secondary task from the highly abstract, laboratory setting used for the initial tests to the current simulated surgical environment.

The current year has seen the further development of the peripheral detection task to accommodate 1) the environmental constraints of testing research participants on an actual surgical trainer and 2) using views from the endoscope that range from traditional single-monitor displays to the large, multi-projector tiled displays being developed for this project. To do this, we have developed a "donut display" (or display annulus) that restricts the peripheral targets to a fixed band that encircles any display that we would like to evaluate. These peripheral targets are now presented independently of the central (laparoscopic) displays allowing for controlled comparisons of workload between radically different display formats.

Our current belief is that the combination of the NASA-TLX and the peripheral detection tasks will form our "gold standard" for workload assessment in a simulated surgical environment. Note that the simulated environment is critical for rapid test and evaluation of new displays during design iterations in our lab. However, we recognize that in an actual surgical environment, the secondary task we are using, although sensitive, is likely to be too intrusive for acceptance by surgeons. Therefore, we are also developing a simpler secondary task for inclusion during actual surgeries. This task involves time estimation. Cognitive engagement in a task redirects mental resources from our normal internal time-keeping and, as a result, people tend to underestimate the duration of lapsed time. This tendency increases predictably with increased mental workload.

Consultation with surgeons at the University of Maryland has indicated that mental "time-keeping", which is an intrinsic part of the self-pacing that characterizes some surgeons' behaviors, will be more readily accepted by this population than other secondary tasks. Our time estimation task is currently being implemented at the University of Maryland for evaluation of workload changes as a function of skill level among surgeons. We intend to compare these results with those we are currently collecting in our lab to validate the tool prior to use in operational evaluations of the REVEAL displays at the University of Maryland.

In addition to the various measures described above, we have also developed a rapid training protocol for allowing nonsurgeon research participants to attain minimal skill in the use of laparoscopic instruments for simple peg-positioning tasks. Such tasks are used in standard assessments of laparoscopic skill, and therefore are part of a battery of tasks we will use in evaluating laparoscopic displays. This training protocol is critical because the use of actual surgeons for every evaluation is prohibitive. Training of five participants with no prior knowledge of endoscopic surgery revealed that acceptable performance levels could be achieved after a two-hour training session. In other words, after our two hour training session, these subjects could be used in initial assessments of workload changes associated with changes in display formats.

Development and Selection of Stress and Situation Awareness Measures

We have been concurrently developing stress and situation awareness measures appropriate for the surgical environment. Although workload is a primary concern, ideal outcomes from display innovations would also involve reduced stress and enhanced situation awareness. We have had success with the Short Stress State Inventory during the testing of our laparoscopic training protocol. This measure is a subjective stress indicator that looks at affective, cognitive, and motivational aspects of stress and is a brief version of the Dundee Stress State Inventory.

Still in the early stages of development is a new measure of situation awareness that should be applicable in a variety of simulated surgical settings (i.e., conventional and laparoscopic). Situation awareness, or the perception and recall of evolving events, is considered critical for planning, decision making, reacting to unexpected events, and recovering from mistakes or accidents. Situation awareness has traditionally been assessed using a procedure that blanks research participants' views of their tasks and requires them to answer a series of questions about what was happening just before the blanking (and what they predict will happen in the near future). Like many of the traditional workload measures, we feel this procedure is too intrusive to use in many surgical contexts. Further, the development of appropriate questions requires time consuming analyses that will have to be repeated for each new surgical task or simulated scenario. Instead, we are exploring the idea that task interruptions per se, without associated questions, could be used to assess situation awareness. That is, when situation awareness is high, recovery from these disruptions should be nearly seamless. We have recently collected data from eight subjects performing a simple video game. We used both traditional and modified situation awareness measures and hope to determine whether the measures are comparable. Data analyses have not been completed at this as we are still collecting data. However, if the new and old procedures provide substantially similar results, then we will recommend the use of the new measure for assessment of possible changes in situation awareness that might accompany changes in operating room technology.

3. Key Research Accomplishments: Project Milestones 2005

The 2005 project plan included two distinct sets of milestones, one for visualization technology development activities, and a second for ergonomic assessment activities. The milestones and our summary of progress in reaching each are assessed in the sections that follow.

Primary Milestones: Visualization Technology

1) Deploy and evaluate first iteration of cluster-based distributed architectural framework

   A cluster-based system with multi-projector OpenGL display capabilities was deployed in the UMMC simulation center. Staff from the UMMC department of general surgery have begun experimenting with the system and provided feedback to the UK-based developers. A system is in place to gather this feedback and use the information to improve the system architecture and implementation.

2) Deploy and evaluate display back-end for probe camera data

   The system deployed at UMMC includes support for input and display of real-time, live video feeds from endoscopic camera probes. Staff from the UMMC department of general surgery have begun experimenting with the display of laparoscopic camera images and provided feedback to the UK-based developers. A system is in place to gather this feedback and use the information to improve the system architecture and implementation.

3) Integrate stereo probe device support into acquisition and back-end display framework

   The "SmartStereo" application developed this year provides an interface for synchronized stereo video streams from stereoscopic laparoscopic camera probes. The synchronized stereo pairs can either be displayed directly using a stereo projection system as we have demonstrated in our lab, or they can be used to perform real-time behind the scenes stereo reconstruction. Software to perform stereo reconstruction and extract measurement information is currently in an advanced stage of development.

4) Design and test algorithms for low-latency probe-data cue extraction (reconstruction, enhancement, overlays)

   As described under "Stereo Probe Calibration," above, we have been developing the necessary framework to calibrate our stereoscopic laparoscope, compute a reconstructed three-dimensional

scene, and extract measurements from a surgical scene reconstructed in this way. We have recently documented the results of the calibration process and analysis of the results of reconstruction in an extended abstract submitted to Computer Assisted Radiology and Surgery.

5) Design and test algorithms for non-invasive ergonomic cue extraction in simulation/surgical setting

   Original plans foresaw the possibility of augmenting externally observed ergonomic data with information that could be inferred from the interior view of the surgical scene. However, a detailed analysis of the capabilities of commercial motion capture systems has lead us to conclude that extraction of information from the interior scene to augment external observations will not be necessary. The Vicon system deployed in the UMMC Simulation Center this year is capable of tracking and recording position in real-time for all of the desired fiducials with sub-millimeter precision.

6) Design display mode alternatives for same-display integration of probe-data, extracted cue data and other overlay information

   Work began this year on architecture and design of a user interface that will integrate real-time probe camera data with additional information sources computed on-line, or computed pre-operatively. The architecture was documented in the journal article "Computing Support for Information-Rich Laparoscopy" (see Publications section for bibliographic reference). Design work is develop a plan to implement the described architecture is ongoing.

7) Test and support performance analysis of trial environment configurations: stereo, display configurations, integrated cues

   The previous section described analytic models developed for performance analysis of REVEAL's display architecture. Experimental work with the current models, and the development of additional models, is ongoing.

Primary Milestones: Ergonomic Assessment

1) Organize performance trials on baseline tasks

   The previous section describes the experimental and computational environment in place in this project year for the measurement of key data in order to assess ergonomic features. Initial experiments and baseline trials demonstrate the equipment and initial findings.

2) Assess latency impact of distributed architecture

   Initial latency analysis on deployed hardware (primarily display system and measurement environment) in progress.

3) Upgrade hardware/software environments

   Visually Immersive Blended Environment (VIBE) display architecture deployed and demonstrated. Integration with measurement environment underway, including latency analysis.

4) Conduct implementation tests on stereo-probe acquisition and display

   Stereo display testing and deployment still in progress (this milestone is not yet complete)

5) Design and perform stereo-based human skills study

Stereo skills tests and baseline performance study still not completed (this milestone is dependent upon a completed milestone 4)

6) Design and test non-invasive assessment algorithms

Complete experimental deployment (Vicon tracking system) at U Maryland and substantial progress on ergonomic assessment models, including cognitive skills testing.

7) Design and perform human skills study with trial environment configurations: display, integrated cues, stereo

Initials human skills study complete to show basic ergonomic features and the correct measurement environment with baseline skills. Complete study with environment configurations not yet completed (studies designed to elicit comparative data between and among configurations)

4. Reportable Outcomes

Outcomes detailed above can be summarize as follows:

1. Experimental System deployment
   We have deployed a complete experimental system and have conducted initial baseline tasks and trials.

2. REVEAL Tool Suite Improvements
   We have improved the REVEAL tools suite in order to support new devices, facilitate installation, and support basic development for endoscopic applications.

3. Stereo Video Display Technology Upgrades
   We have implemented stereo display technology in the laboratory and have upgraded display surfaces and polarization capabilities.

4. Stereo Probe Calibration
   We have implemented and tested stereo calibration algorithms for integrating measurement capabilities into the laparoscopic environment. These results can be used to solve open problems such as through-the-lens (direct) measurement of features.

5. Performance Modeling and Analysis
   We have conducted a detailed analysis of the system performance of the distributed computing environment (which supports VIBE, the tile-based display system). These latency data reveal specific points in the system where bottlenecks occur and where improvements can be made.

6. Enhanced Experimental Tools for Cognitive Ergonomics Experiments
   We have produced a set of cognitive metrics for experimentally assessing features such as mental workload.

5. Conclusions

We have established an extensive software and hardware platform for the measurement of both cognitive and physical ergonomic factors in laparoscopic surgery. This environment contains several new technologies being developed under this contract, including a scalable, flexible tile-based display system, calibration algorithms for stereo scopes, and a distributed architecture in which to perform computations. The information technology development team has worked closely with the clinical team at the University of Maryland to set up an experimental space which we have used to conduct initial experiments. The data from these experiments are summarized above and are reported in the literature. We report that project milestones were substantially completed during this reporting period.

6. References

Publications referenced in this report are listed in the bibliographic section of the appendix (appendix C). One publication is attached as the final appendix.

7. Appendices

Appendix A: Project Personnel

Name	Role	Location	2005 FTE
W. Brent Seales, PhD	Principal Investigator	UK College of Engineering	30%
Adrian Park, MD	Co-Principal Investigator	UM School of Medicine	10%
Steve Bailey	Media Specialist	UK Department of Computer Science	100%
Tsegay Baraki	Administrative Support (Budget, Reporting)	UMMS Department of General Surgery	40%
Jesus Caban	Research Assistant	UK Department of Computer Science	50%
C. Melody Carswell	Senior Researcher	UK Department of Psychology	20%
Duncan Clarke, PhD	Technical Project Lead	Fremont Associates, LLC	60%
Ryan Davis	Student Programmer	UK Center for Visualization	25%
Praveen Devabhaktuni, MS	Program Systems Analyst	UK Center for Visualization	100%
Ivan George	Technical Support	UMMS Department of General Surgery	20%
Kimberly Hall	Administrative Support (Budget, Clerical)	UK Center for Visualization	20%
Stephen Kavic, MD	Senior Researcher	UM School of Medicine	20%
Gyusung Lee		UM School of Medicine	50%
Linda Rice, RN, CCRC	Administrative Support (Research Protocols)	UK Medical Center	20%
Ross Segan, MD	Senior Researcher	UM School of Medicine	10%
Robert Shapiro, PhD	Senior Researcher	UK Department of Kinesiology and Health	10%
Yogesh Shukla, MS	Program Systems Analyst	UK Center for Visualization	100%
Donald Witzke, PhD	Senior Researcher	UK Department of Pathology	5%

Appendix B: Laboratory Facilities (UK)

- Project Staff Office
  - Location: 801 KU Building
  - Purpose: Working environment for day-to-day activities of software developers.
  - Equipment:
    - Two developer workstations
    - Media workstation
    - Twin-processor Dell PowerEdge server with DLT tape drive
    - Cisco firewall/router

- High-Performance Multi-Projector Display Laboratory
  - Location: 871 KU Building
  - Purpose: Test environment for MIS video image processing techniques and large-scale projected displays.
  - Equipment:
    - RackSaver 22 Processor cluster computer with gigabit backplane
    - Dell workstation
    - Gigabit network switch
    - 12 DLP projectors with overhead mounts
    - Custom heat- and vibration-tolerant filters w/ mounts for stereo projection
    - 7.5' x 10' back-projected polarity-preserving screen with mounting frame
    - General purpose Canon video camera
    - Stryker trainer stand with auxiliary high-definition LCD display
    - 2 Stryker 888 high resolution cameras, controllers and lens probes
    - Stryker light source
    - Viking Systems stereo camera probe, controller and light source
    - Assorted MIS surgical instruments

- Project Office
  - Location: 883 KU Building
  - Purpose: Working environment for project management and small team meetings.
  - Equipment: One general purpose computer.

- Web site
  - Location: http://halsted.vis.uky.edu
  - Purpose: Provide general overview of project activities, distribute project documents and software, and serve as repository for project images (still and video).

Appendix C: Publications

[1] Carswell, C., Clarke, D. and Seales, W., “Assessing Mental Workload during Laparoscopic Surgery.” *Surgical Innovation*, Volume 12, Number 1 (March) 2005: pp. 80-90.

> While the use of performance efficiency measures (speed, movement economy, errors) and ergonomic assessments are relatively well established, the evaluation of cognitive outcomes is rare. This paper makes the case for assessment strategies that include mental workload measures as a way to improve training scenarios and training/operating environments. These mental workload measures can be crucially important in determining the difference between well-intentioned but subtly distracting technologies and true breakthroughs that will enhance performance and reduce stress.

[2] Seales, W. and Clarke, D., “Computing Support for Information-Rich Laparoscopy." *Surgical Innovation*, Volume 12, Number 4 (December) 2005.

> Developments in the architecture and organization of high-performance general-purpose computer systems are largely ignored by the technology infrastructure of the modern laparoscopic surgical suite. The current state of technology for laparoscopy is a camera and monitor linked via a controller that distributes analog or digital video signals without regard to their content. This article discusses the opportunities that will be created by inserting general-purpose high-performance computing into the information stream between camera and display. We envision that the use of this technology will radically transform laparoscopy from its current state as “surgery by pictures” into an entirely new, information-rich surgical environment.

[3] Seales, W. and Clarke, D., “Calibration of Stereoscopic Endoscope for Measurement and Multi-Modal Registration.” Submitted to *CARS 2006—Computer Assisted Radiology and Surgery—20th International Congress and Exhibition*, June 2006, Osaka, Japan.

> A Stereoscopic Endoscope is an endoscope with two optical paths, either separate or shared, creating two images related to one another by a measurable disparity shift. Such an endoscope can be used to generate a stereoscopic view for a surgeon, as with the DaVinci robot in use today. In order to use such an endoscope for metric measurement of structures in the operative field, it is necessary to calibrate the dual optical paths according to a camera model. Once calibrated, it is possible to use stereo reconstruction in order to recover Euclidean metric measurements from the endoscopic images. This measurement capability is extremely valuable in a number of contexts where it is otherwise difficult to gauge the size and scale of the operative field.
>
> In this work we report calibration results for a stereoscopic endoscope that support the ability to make instantaneous measurements in the image from a single stereo pair. Our initial experiments also indicate that a the stereo measurement accuracy can be improved by combining the estimates from stereo pairs with monocular-view structure-from-motion estimates derived from tracked features over a number of frames.

[4] Lee G, Weiner M, Kavic SM, George IM, Park AE, “Pilot study – Correlation between postural stability and performance time during fundamentals of laparoscopic surgery (FLS) tasks,” Annual Conference of the Association of Surgeons of Great Britain and Ireland (ASGBI) in 2006 (accepted)

[5] Lee G, Weiner M, Kavic SM, George IM, Park AE, “Joint kinematics vary with performance skills during laparoscopic exercise [Fundamentals of Laparoscopic Surgery (FLS) task 1],” Annual Conference of Digestive Disease Week in 2006 sponsored by the Society for Surgery of the Alimentary Tract (SSAT) (submitted)

[6] Weiner M, Lee G, Weiner M, Kavic SM, George IM, Park AE, “Analysis of range of motion at the wrist joint with MIS surgeons during Fundamentals of Laparoscopic Surgery (FLS) exam,” Annual Conference of the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) in 2006 (accepted)

[7] Lee G, Weiner M, Kavic SM, George IM, Shapiro R, Park AE, "Postural instability does not necessarily correlate to poor performance," Annual Conference of the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) in 2006 (accepted)

[8] Wu G., et al, "ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion – Part II: shoulder, elbow, wrist and hand," Journal of Biomechanics, 38, p 981-992, 2005

Computing Support for Information-Rich Laparoscopy

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November 8, 2005

Abstract

Developments in the architecture and organization of high performance general purpose computer systems are largely ignored by the technology infrastructure of the modern laparoscopic surgical suite. The current state of technology for laparoscopy is a camera and monitor linked via a controller that distributes analog or digital video signals without regard to their content. This article discusses the opportunities that will be created by inserting general purpose high performance computing into the information stream between camera and display. Using this technology we envision a radical transformation of laparoscopy from its current state as "surgery by pictures" into an entirely new, information-rich surgical environment.

1 Introduction

Consider the evolution of sports broadcasting over the last thirty years. A football broadcast, circa 1970, consisted of a low-resolution video image of the playing field, voice-over and the occasional superimposed game score or play-clock value. Now, fast-forward to today's HDTV broadcast with constantly updated information fields and key game information superimposed visually on the playing field. The line of scrimmage in red, a line across the field indicating the position of the first down marker in yellow, broadcaster-specific advertising images appearing on virtual banners along the sidelines.

Non-invasive, information rich displays of the game have enhanced the viewing experience for home viewers without requiring any on-field support; the very literal "line" of scrimmage that you see on your screen doesn't require anyone to walk out on the field and paint the grass. These enhanced views are made possible through the application of computer image processing techniques.

Now, consider the state of the art in displays for laparoscopic surgery; a low resolution video image (evolving toward HDTV) is routed directly from a camera to a monitor. There are occasional informational displays related to the state of the laparoscopic hardware, but no real augmentation of the displayed image to support the surgeon. Clearly, the laparoscopic surgeon could benefit from information enriched displays every bit as much as the sports fan, yet the state of the art in laparoscopic displays is thirty or more years behind sports broadcasting.

The two main impediments to this evolution in technology are (1) the lack of a standard, open computing infrastructure in the data stream between camera and display; and (2) the lack of

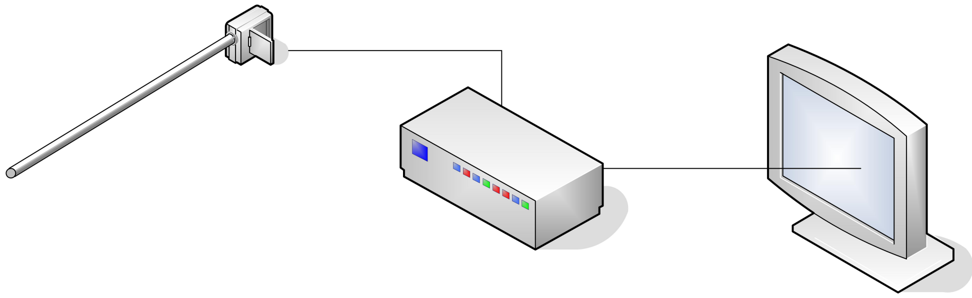

Figure 1: Current architecture for laparoscopic display

available display area for the presentation of additional information, while preserving the present level of video fidelity.

In this paper we present a general purpose system architecture to support the evolution of laparoscopic surgery away from "surgery by pictures" toward an entirely new, information-rich surgical environment. The architecture will be based on low-cost, open, extensible components that will provide the flexibility needed to support a diverse range of enhanced views. These views will be based on information sources such as pre-operative scans, enhanced intraoperative imaging, and other on-line information sources.

The remainder of this paper is organized as follows. Section 2 proposes a hardware and software architecture to support an information-rich surgical environment. Section 3 will describe applications enabled by the proposed architecture. Section 4 presents a case study based on a prototype environment deployed in the University of Maryland Medical Center's simulation environment. Section 5 will conclude the paper with summary remarks.

2 Architecture

Figure 1 presents an abstract view of the typical laparoscopic display system. As shown, (1) a camera captures video images of the surgical site, (2) sends that stream of images to a controller which may provide low-level image enhancement features such as white-balance calibration, brightness, and color reproduction adjustments, and (3) the controller distributes the output video signal to one or more display devices. This system has several virtues, including the following:

- *Simplicity of architecture*—Vendor supplied systems consist of a small number of components that interconnect through simple physical interfaces. The skills needed to set up and support such systems are minimal.

- *Simplicity of interface*—Since the systems provide only one function, *i.e.,* display of video from a laparoscope, the user interface is limited to switching the unit on and off, and minor set-and-forget adjustments for brightness, *etc.* Otherwise the only user control is the physical motion of the camera to provide the desired view.

- *Low latency*—The term *latency* refers to the time delay introduced between the capture of a video frame and its presentation on the display device. Since current systems are so simple in their design and operation, the latency they introduce is not typically noticed by the user.

Latency does exist, however, in the form of delays due to digital-to-analog conversion at the camera, image processing in the controller, analog-to-digital conversion at the display device, and small propagation delays throughout the chain from camera to display.

- *Interoperability*—Cameras and controllers are typically interconnected using a proprietary interface. However, once the controller has converted the video into standard video signals and presented the signal on standard connectors any standard video device can be used to capture or display the signals.

However, along with these virtues come severe limitations on the ability to enhance the presented image:

- *No capacity for additional information sources*—Current systems do not provide any way to access additional data sources such as pre-operative scans. The only input to the system is the image stream from the camera probe.

- *No capacity for image processing*—The only image processing stage in current systems is the limited video processing that takes place inside the controller. Controllers are provided as a closed system, not allowing adaptation or enhancement.

- *No flexibility in display*—Current systems map the captured video image directly to the entire frame of a video display. This configuration doesn't leave any screen area to be used for displaying added information, and limits displayed images to those that can be shown on a conventional video display. Thus, it is not possible to present enhanced images, such as polarized stereo.

Since January of 2004 the Reconstruction, Enhancement, Visualization and Ergonomic Assessment for Laparoscopy project (REVEAL) at the University of Kentucky's Center for Visualization and Virtual Environments has been researching image processing and display technologies to improve the practice of laparoscopic surgery. In the course of this work we have evolved a new system architecture that attempts to address the limitations of existing systems while retaining their virtues that are consistent with the creation of an information-rich environment.

The system architecture we propose is shown in Figure 2. It consists of hardware as well as software components that will facilitate the enhancement and augmentation of captured images. At a high level, the key components are (1) one or more cameras, either monocular or stereoscopic; (2) an image processor capable of receiving multiple input sources and constructing new, synthetic images that represent meaningful enhancements to the video input stream; (3) an interaction station where the surgeon can be assisted in the manipulation of images by a staff member working outside of the sterile surgical field; and (4) an extensible, projected display that will allow the image size and/or pixel density of displayed images to be varied to suit task requirements.

The subsections that follow describe the hardware and software components of this system architecture.

2.1 Hardware

As shown in Figure 3, the hardware environment consists of (1) one or more cameras (monocular or stereoscopic) providing a stream of video images of the surgery; (2) dedicated controllers for

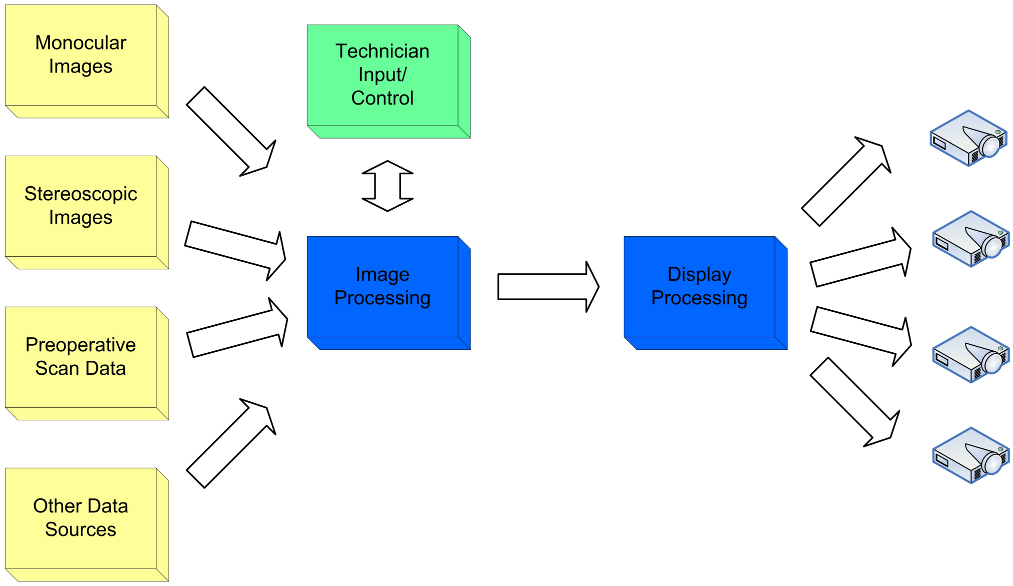

Figure 2: The REVEAL system architecture

bridging video data onto the backbone network; (3) general purpose computing nodes for image processing, data processing, and image composition; (4) a generic, non-sterile workstation for control of algorithms and data streams; and (5) special purpose image processing hardware for taking processed images off the network, segmenting them and outputting the segments to casually aligned projectors for display.

Each of these components can be created using commercial, off the shelf (COTS) technology or application specific custom developed hardware, depending on the performance requirements and cost constraints of the environment being created. Key design constraints when provisioning such a system are as follows:

- *Availability of input streams with meta-data*—Input streams, be it laparoscope video, preoperative scan data, or other information sources, must be interfaced to the system in a way that presents data to the system with predictable real-time performance. Not all data must be received instantaneously after its creation, but the system must have a reliable, quantitative way of understanding the temporal quality of data in terms of frame rate, latency, jitter, *etc.*

- *Network connectivity, throughput and latency*—Since the backbone network is central to the hardware system, its performance will be critical to the overall quality of service delivered by the system. It must be possible to connect high-resolution data sources to computing nodes, and computing nodes to image processing nodes in a way that will deliver the necessary throughput with minimal latency.

- *Overall performance*—Laparoscopic surgery is a closed-loop; *i.e.,* images are used by the surgeon to decide how to move the instruments, and the instrument motions appear in the images which are viewed by the surgeon. Any human in the loop closed loop control system must function with latency that is below the 200ms level [3, 5, 8, 9]. Latency above that level will result in degraded performance.

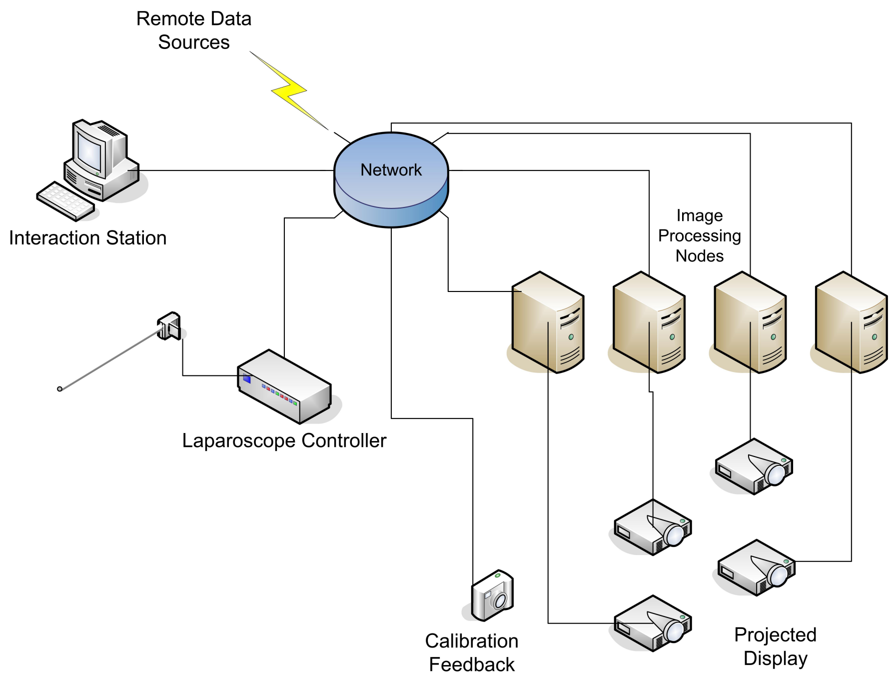

Figure 3: The REVEAL hardware architecture

Throughput will also be critical; *i.e.,* the rate at which the system is able to display image frames. Current technology presents information at the standard rate of thirty frames per second. Image processing must not degrade throughput to the point that a low frame rate makes the image appear "jumpy" rather than fluid.

- *Display fidelity*—Typical COTS projectors are optimized for applications like PowerPoint presentations. Their use for laparoscopic image display can be problematic if steps are not taken to control for variations in color representation, variations in overall brightness between projectors, variations in brightness across bulb life, variations in pixel geometry between projectors, *etc.*

2.2 Software

As shown in Figure 4, the key components of the software architecture are (1) a laparoscopy workbench tool for integrating data streams and controlling algorithms, and (2) a distributed rendering environment for segmenting and displaying images using casually aligned projectors.

The interface of the laparoscopy workbench will be presented at the non-sterile workstation. A technician will aid the surgeon by selecting data sources, inputting parameters to control image processing algorithms, and manipulating images in real-time at the direction of the surgeon. The workbench will be implemented using an open architecture that will allow independent development of features that can be incorporate at run-time as *plug-ins.*

Our distributed rendering environment uses sensor feedback to automate the calibration of casually aligned projectors to form a single, blended display surface [4, 7, 1]. A pre-surgery calibration phase will project a calibration pattern using each projector, and video images captured by cameras

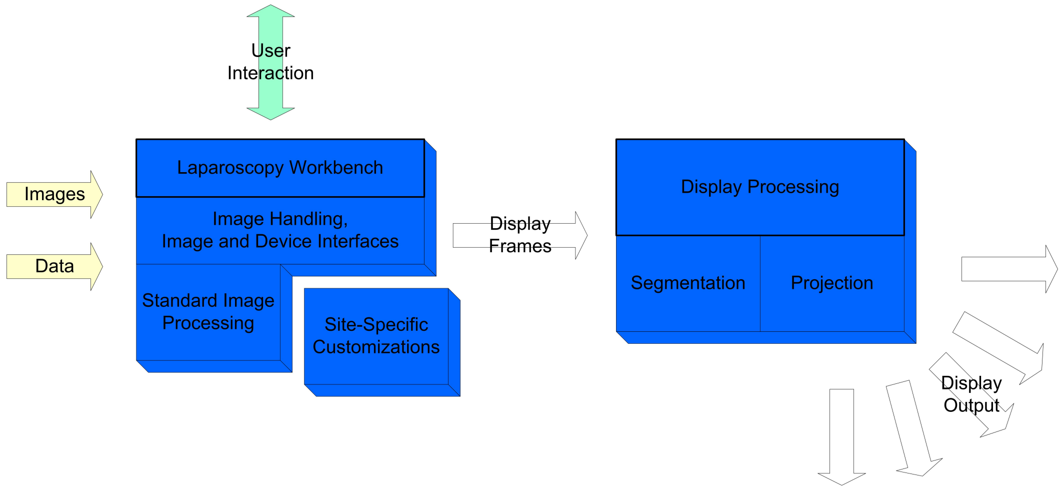

Figure 4: The REVEAL software architecture

observing the display will be used to compute necessary transformations to align image segments and blend their intensities in real-time. During the surgery the use of multiple image processing nodes to display the partitioned image will improve throughput and latency by distributing the rendering workload across multiple nodes, each having a direct connection to a single projector.

3 Applications

The laparoscopy workbench will be a framework for creating plug-in modules that provide functionality on an as-needed basis during the surgery. The framework will provide a standard interface to (1) video streams, still image data, XML-encoded data streams, *etc.*; (2) access to standard user interface devices such as keyboard, mouse, foot pedals, *etc.*; and (3) low-level application programming interfaces to classic image processing algorithms.

Within this framework users will create plug-in modules that implement specific functionality. Modules that we envision include the following:

- *Image fusion*—The two-dimensional, real-time image of anatomy captured by the laparoscope lacks the three-dimensional structural information of CT, MRI or even X-Ray imaging. Merging of off-line scan data with real-time video images would allow the surgeon to see into or around anatomy to better understand structure before making critical incisions. A long-term goal of real-time registration of volumetric scan data with the images for the surgery as it is happening may be unrealistic for the near term, but even off-line registration of still images from the surgery with pre-operative scans in near real-time could provide critical information to the surgeon intraoperatively.

- *Real-time video conferencing*—A larger display space, only partly occupied by the images from the laparoscope, would provide a tableau for adding other information sources. For example, we could envision a virtual desktop displaying full-resolution, full-size laparoscope images along side images from a real-time video-teleconference consultation with colleagues, or interactive display of medical students at remote locations during an interactive web-cast.

- *Heads-free stereoscopic views*—Current COTS technology for minimally invasive surgery using stereoscopic views is based on a head-mounted display that uses a pair of small LCD screens to present independent views to each of the surgeon's eyes. Wearing the head-mounted display is both physically cumbersome, and potentially disruptive to the surgeon's interaction with other members of the surgical team.

  Using projected displays with polarizing filters to control the polarity of the light creating images for the left and right eyes, stereoscopic views can be presented to the entire surgical team. Rather than having to wear heavy, wired headsets the team can simply wear lightweight polarized sunglasses. When viewing the display made up of polarized light, the wearers will perceive distinct images at their left and right eyes. When viewing objects illuminated by non-polarized light, they will observe a normal scene with only slight attenuation of the scene's brightness.

- *Non-invasive linear measurement*—The availability of low-cost stereoscopic laparoscopes facilitates the reconstruction of three-dimensional anatomy from stereo image pairs. These stereo image pairs need not be displayed in stereo to the end user to be of value; the reconstruction of three-dimensional anatomy can be used internally to the workbench to provide quantitative dimensional information about the surgical site.

  In laparoscopic ventral and incisional hernia repair [6, 2], a small patch of mesh is sewn into the abdominal wall to repair the defect that allowed the herniation to occur. Intraoperatively, the size of the defect must be determined so that a mesh patch of the proper size can be introduced into the surgical site through a trocar. The determination of the dimensions of the defect is currently performed using a tape measure, manipulated using graspers. This operation is tedious, time consuming, and requires the introduction and removal of the tape to perform the measurement.

  Using a stereoscopic laparoscope and real-time reconstruction of the three-dimensional anatomy will allow measurements to be taken using virtual measuring tapes. The surgeon will direct the camera at the defect to be measured, and the assisting technician will indicate the limit points of the defect on the image of the anatomy. Image processing algorithms will then locate the indicated points on the reconstructed anatomy and report the exact distance between points. All of this will take place in the digital domain with just a few manipulations of the controls of the laparoscopic workbench.

4 Case Study: Heads-free Stereoscopic Display

We have created a heads-free stereoscopic display based on an early prototype of the architecture described. The system consists of (1) a Vista Surgical 10mm stereoscopic endoscope; (2) a Vista Surgical camera controller; (3) digital video link from the camera controller to a general purpose workstation designated the "head node" of the display cluster; (4) a high-density cluster of computers equipped with independent display driver hardware; and (5) eight off-the-shelf SVGA video projectors equipped with polarizing filters. Observers wear lightweight, low-cost polarized glasses to view the projected images.

System throughput supports a frame rate of 15-20 frames per second. Latency is in the range of 120-165ms. Figure 5 presents the processing stream from capture to display. Note that latency

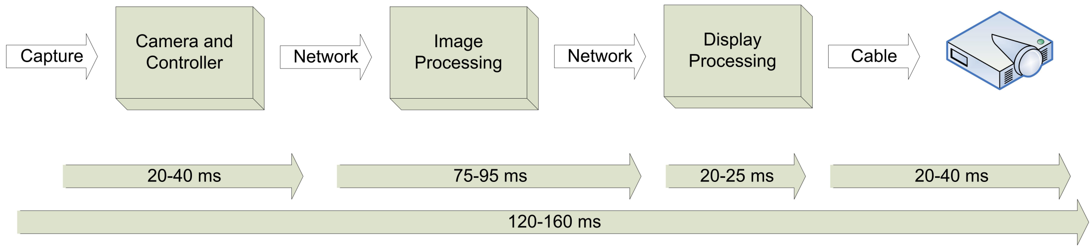

Figure 5: Heads-free Stereoscopic Display System

of the overall system contains a large component due to latency introduced by the camera and projector. This is baseline latency that exists in current camera/display configurations.

In our laboratory we used a polarity-preserving back-projected screen and two sets of four projectors to create a stereo video display measuring approximately six feet by four feet. The use of multiple projectors to illuminate the display area insured that image brightness was not negatively impacted by the relatively large display area.

5 Summary

In this article we have presented a high level system architecture to present information-rich displays during laparoscopic surgery. The system is flexible and extensible, and self-calibrates the display area using video feedback allowing projectors to be set up without elaborate preconfiguration. The software architecture allows plug-and-play compatibility between software modules developed independently of one another.

The creation of information rich displays aims to replace some of the information lost in the move away from open surgery toward minimally invasive procedures. We expect such displays to have a quantifiable impact on patient time under anesthesia, and the cognitive workload imposed on surgeons during surgery.

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